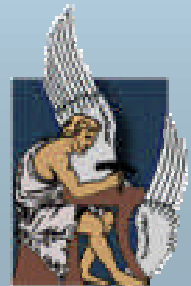# AUTONOMOUS NAVIGATION & COLLISION AVOIDANCE SYSTEM
FOR THE NEARHOS UAV

STN ATLAS – 3 SIGMA & Technical University of Crete

Collaboration Project

Presented by:

Prof. Kimon Valavanis

1. REPORT DATE **02 SEP 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Autonomous Navigation & Collision Avoidance System For The Nearhos UAV**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **STN ATLAS 3 SIGMA & Technical University of Crete**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES **See also ADM001676, UAV 2002 Conference & Exhibition., The original document contains color images.**

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **UU**	18. NUMBER OF PAGES **32**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

STN ATLAS ⊕ 3 SIGMA

NEARCHOS UAV SYSTEM
OPERATIONAL - TECHNICAL CHARACTERISTICS

STN ATLAS ELEKTRONIK

WING SPAN:	5.10m
WING AREA:	2.95m^2
OVERALL LENGTH:	3.95m
MAXIMUM TAKE-OFF-WEIGHT:	190kg (tricycle take off)
	110kg (by catapult)
MAXIMUM PAYLOAD:	51-92kg
OPERATIONAL SPEED:	75 - 220km/h
OPERATIONAL RANGE:	100 km
FLIGHT ENDURANCE:	8-12 h
OPERATIONAL ALTITUDE:	100 - 7000 m
TAKE OFF:	TRICYCLE / CATAPULT
RECOVERY:	TRICYCLE LANDING / PARACHUTE
PROPULSION UNIT:	WANKEL 38 BHP/7800 RPM

NEARCHOS UAV SYSTEM

Existing NEARCHOS Flight Control System (FCS)

STN ATLAS
ELEKTRONIK
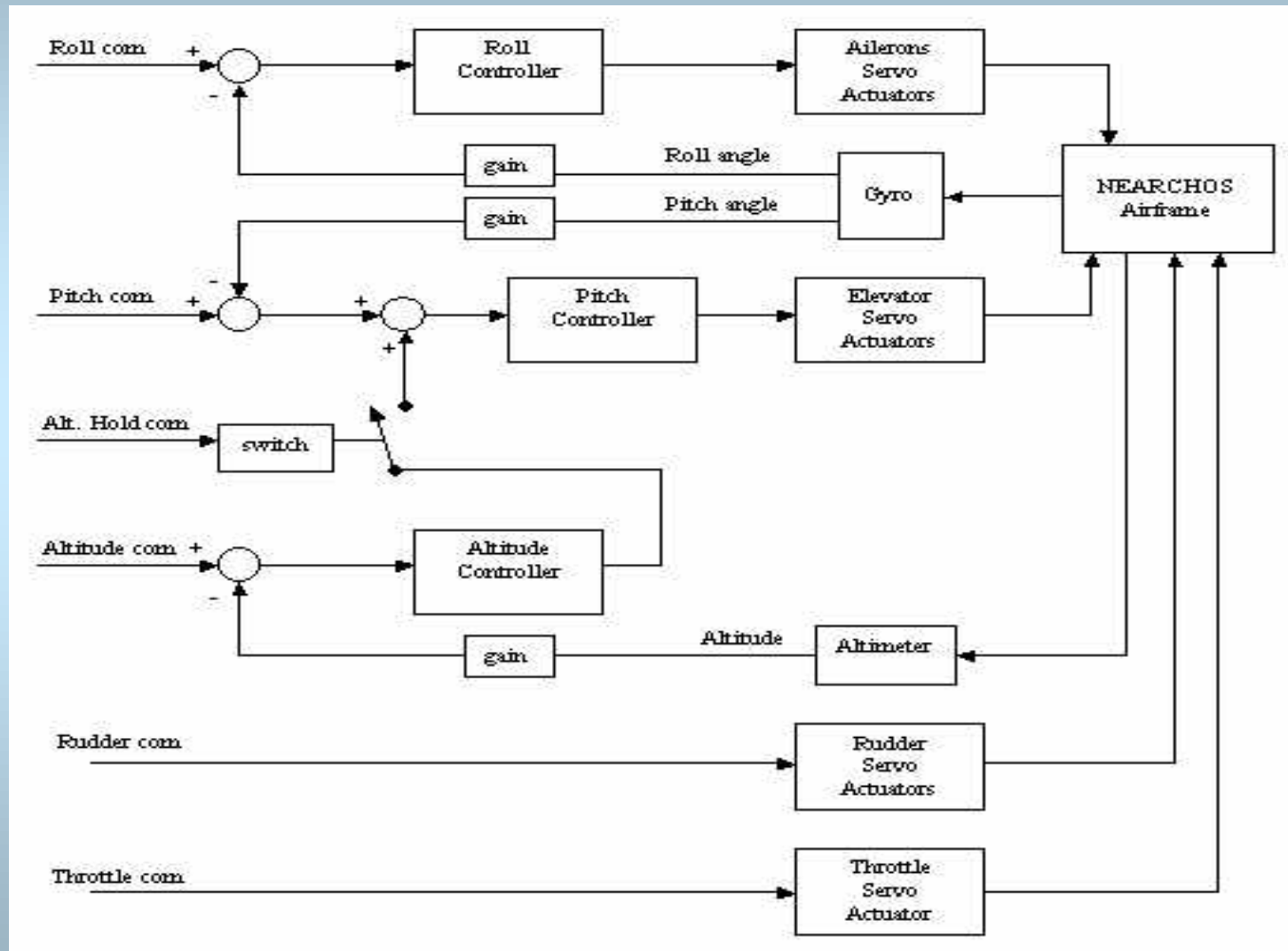
Initial NEARCHOS Flight Control System
(commands transmitted via RF communication links)

Roll control by controlling the ailerons servo actuators.

Pitch control by controlling the elevator servo actuators.

- – when altitude hold is activated, a signal proportional to the difference between commanded and actual flight altitude is added to the commanded pitch angle.

Throttle and rudder control are open loop.

Roll and pitch feedback loops help maintain stability but also result in different operation of the control sticks (control commands) compared to a general aviation aircraft, i.e.:

- – a constant pitch (roll) stick deflection results in maintaining pitch (roll) attitude at the commanded level, instead of producing aircraft pitching (rolling) at a constant rate.

Autonomous Navigation System (ANS) – Integration with the initial FCS

NO MODEL AVAILABLE - (no aerodynamic derivatives).

Neurofuzzy design procedure: offline controller parameters training using data from manually controlled flights (the controller "learns" to act like the operator)

Modular design: parallel operation of individual controller modules

Criteria: simpler controller structures – fast controller operation – ability to design/modify/replace controller modules individually

Inputs:

Gyro (roll and pitch angles) and engine RPM sensor readings
Desired altitude and airspeed (predefined flight profile data)
Heading and altitude errors (calculated on-line using predefined flight profile data together with GPS and altimeter readings)

Outputs: commands to the NEARCHOS FCS

ANS Operation Principles

Desired flight profile - time series of waypoints in the 3-D space with desired airspeed when approaching a waypoint.

Data as *(x, y, z, v, t)*, where *x, y, z*: waypoint latitude, longitude, altitude, and *v, t*: waypoint approach airspeed and time.

At a time instant, the ANS calculates the appropriate commands to the AV flight control system as a function of the deviation from the present waypoint (expressed by means of heading and altitude errors) and AV state variables.

Heading error: difference between the desired and actual AV heading (when positive, a right turn is desired). Desired heading: direction from the actual to the desired AV position in the XY-plane.

The actual AV position and heading are provided by the GPS receiver, while the actual AV altitude is provided from the altimeter of NEARCHOS.

ANS Neurofuzzy Controllers Design

- Training set based on recorded manual flight data and organized as controller input-output pairs.

- Controller outputs (control commands to the NEARCHOS FCS) are directly available from recorded data.

- Preprocessing of recorded data is necessary to produce most of the controller inputs during the design procedure, since no flight profile is predefined during a manual flight.

- Assumption: the desired waypoint at time t_0 is defined from the flight data at time t_0+10 sec.

- This assumption means that flight data at time t_0+10 are considered as the desired data at time t_0. Thus, calculation of controller inputs at time t_0 is possible after applying the necessary preprocessing on the recorded manual flight data.

- Test data sets, used for evaluation of designed controllers, are also created in the same way from parts of recorded flights.

ANS Neurofuzzy Controllers Structure
(with input-output linguistic variables)
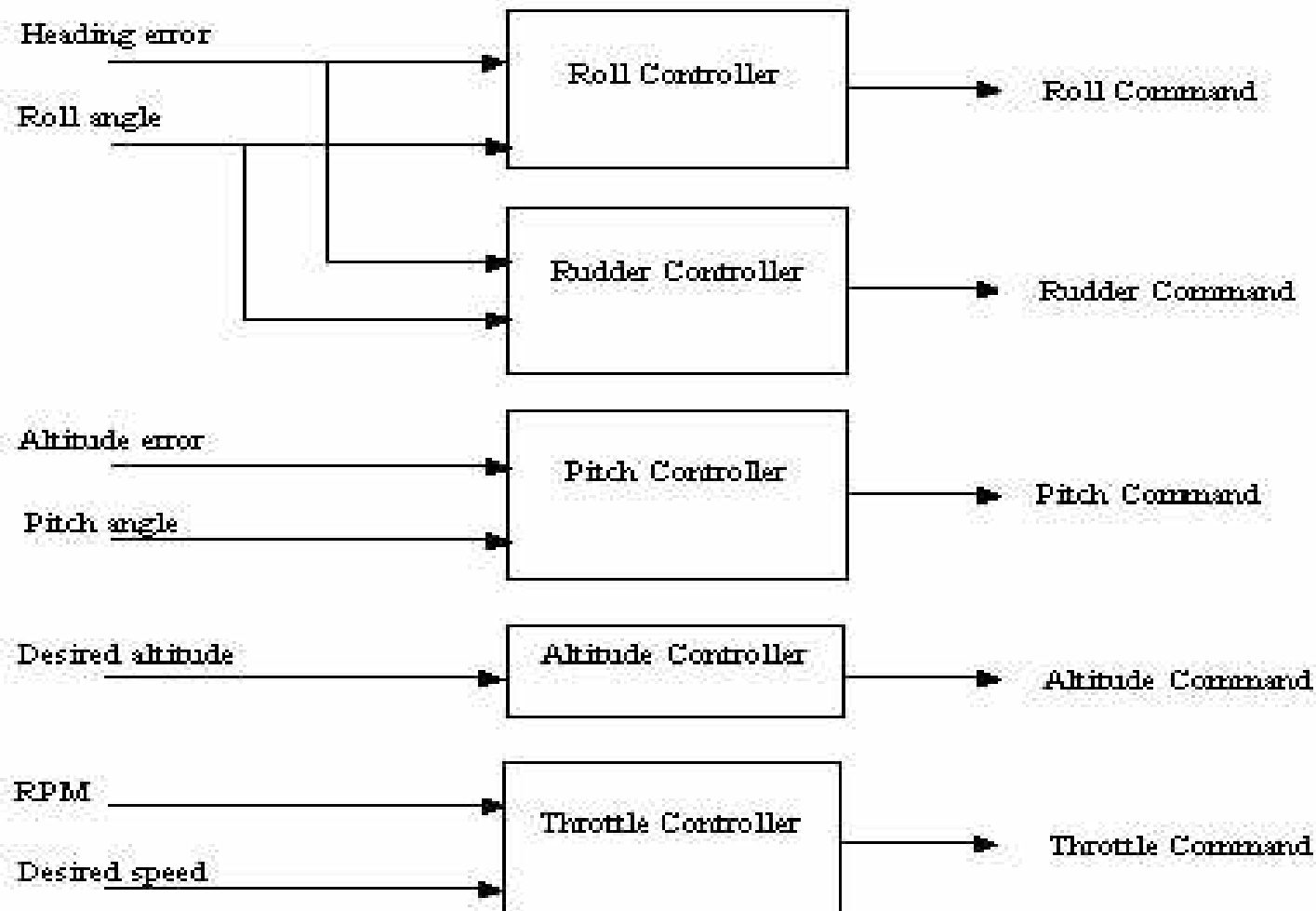
ANS Neurofuzzy Controllers Design

- Training and test sets for Roll and Rudder controllers (lateral control) are created using data from the same parts of recorded flights. The same holds for Pitch and Altitude controllers (longitudinal control).

- Implementation using MATLAB Fuzzy Logic Toolbox.

- Type of designed NF controllers: **zero-order Sugeno**, i.e. the rule base of each controller contains rules of the form

$$IF\ x1\ is\ A\ AND\ x2\ is\ B\ THEN\ y_i = c_i$$

  where c_i: constant

- Membership Functions (MFs) of the input variables: Gaussian

- The limit values of all input variables (MFs range) are selected according to the minimum and maximum input variable values in the training set.

- AND operator: product - Defuzzification: weighted average

  NOTE: First-order Sugeno type controllers were also designed, but showed inferior generalization capabilities.

Roll Controller

- Inputs: heading error and roll angle (*headerror* and *phi*)

- Output: roll command to the FCS of NEARCHOS (*rollcom*)

- *phi* takes values in the interval $[-70^o, 70^o]$. Roll angle values outside this range are unlikely to occur in normal flight conditions of NEARCHOS

- *headerror* takes values in the interval $[-100^o, 100^o]$. Heading error values calculated during operation are limited to the interval $[-100^o, 100^o]$ (by definition, heading error may take values in the interval $[-180^o, 180^o]$).

- Controller rule base: 35 rules of the form

If *headerror* is A1 and *phi* is A2 then *rollcom* is c_i

where A1: nb, nm, ns, Z, ps, pm, pb, A2: nb, ns, Z, ps, pb and c_i: constant

Rudder Controller

- Inputs: heading error and roll angle (*headerror* and *phi*)

- Output: rudder command to the FCS of NEARCHOS (*ruddercom*)

- Controller rule base: 35 rules of the form

    If *headerror* is A1 and *phi* is A2 then *ruddercom* is c_i

 where A1: nb, nm, ns, Z, ps, pm, pb, A2: nb, ns, Z, ps, pb and c_I: constant

NOTE: Rudder control was not applied during the manual flights used for training data set construction. This results in keeping the rudder command practically constant for any value of the input variables

Pitch Controller

- Inputs: altitude error and pitch angle (**alterror** and **theta**)

- Output: pitch command to the FCS of NEARCHOS (**pitcom**)

- **theta** takes values in the interval $[-20^o, 45^o]$. Pitch angle values outside this range are unlikely to occur in normal flight conditions of NEARCHOS

- Controller rule base: 25 rules of the form

If **alterror** is A1 and **theta** is A2 then **pitcom** is c_i

where A1: nb, ns, ps, pm, pb, A2: nb, ns, ps, pm, pb and c_I: constant

Altitude Controller

- Input: desired altitude (*desalt*)

- *desalt* takes values in the interval [100m, 500m] (the manual flights used for training data set construction were performed in low altitude)

- Output: altitude command to the FCS of NEARCHOS (*altcom*)

- Controller rule base: 5 rules of the form

If *desalt* is A1 then *altcom* is c_i

where A1: low, mlow, medium, mhigh, high and c_I: constant

Throttle Controller

- Inputs: engine RPM and desired airspeed (**RPM** and **dspeed**)

- **dspeed** takes values in the interval [20, 70] (m/sec)

- **RPM** takes values in the interval [5000, 8000]

- Output: throttle command to the FCS of NEARCHOS (**thrcom**)

- Controller rule base: 9 rules of the form

If **RPM** is A1 and **dspeed** is A2 then **thrcom** is c_i

where A1: low, med, high, A2: slow, normal, fast and c_I: constant

Real-Time Data from Test Flight

ANS Controller Outputs – Manual Commands (Test Flight)
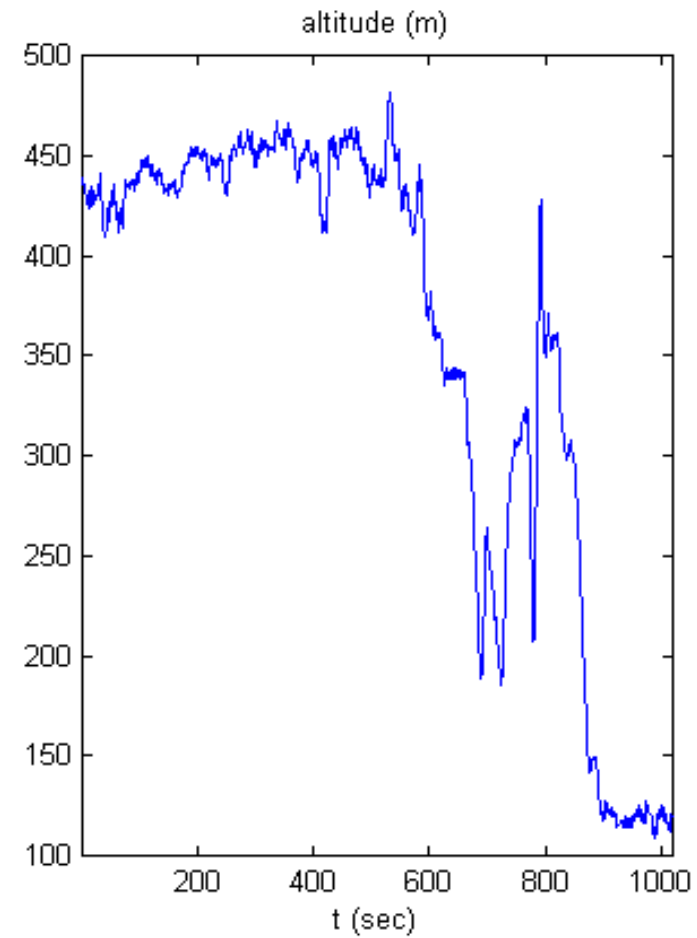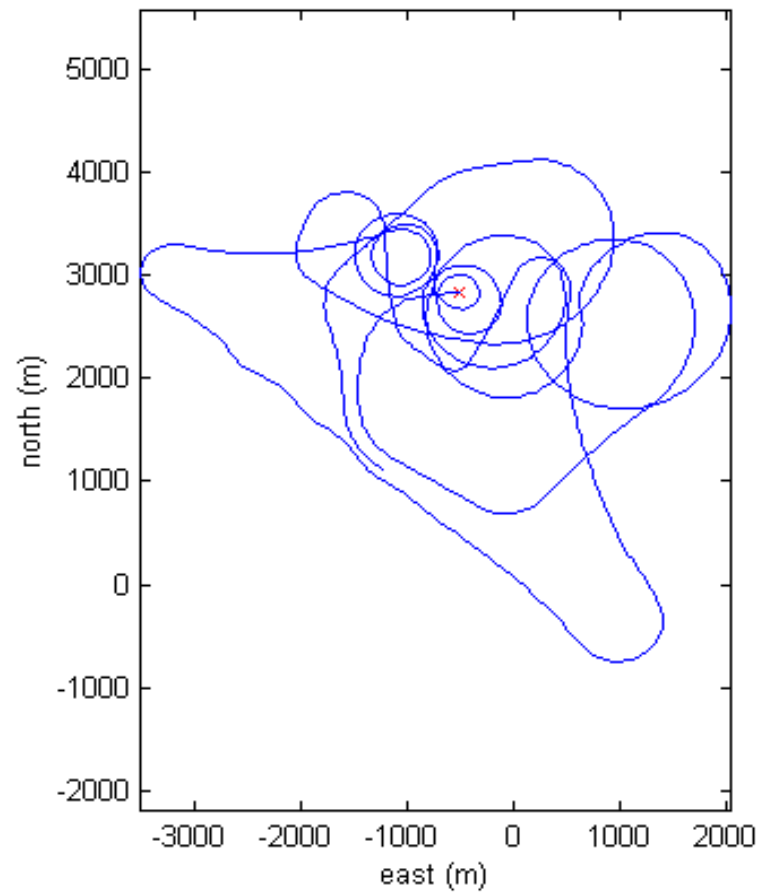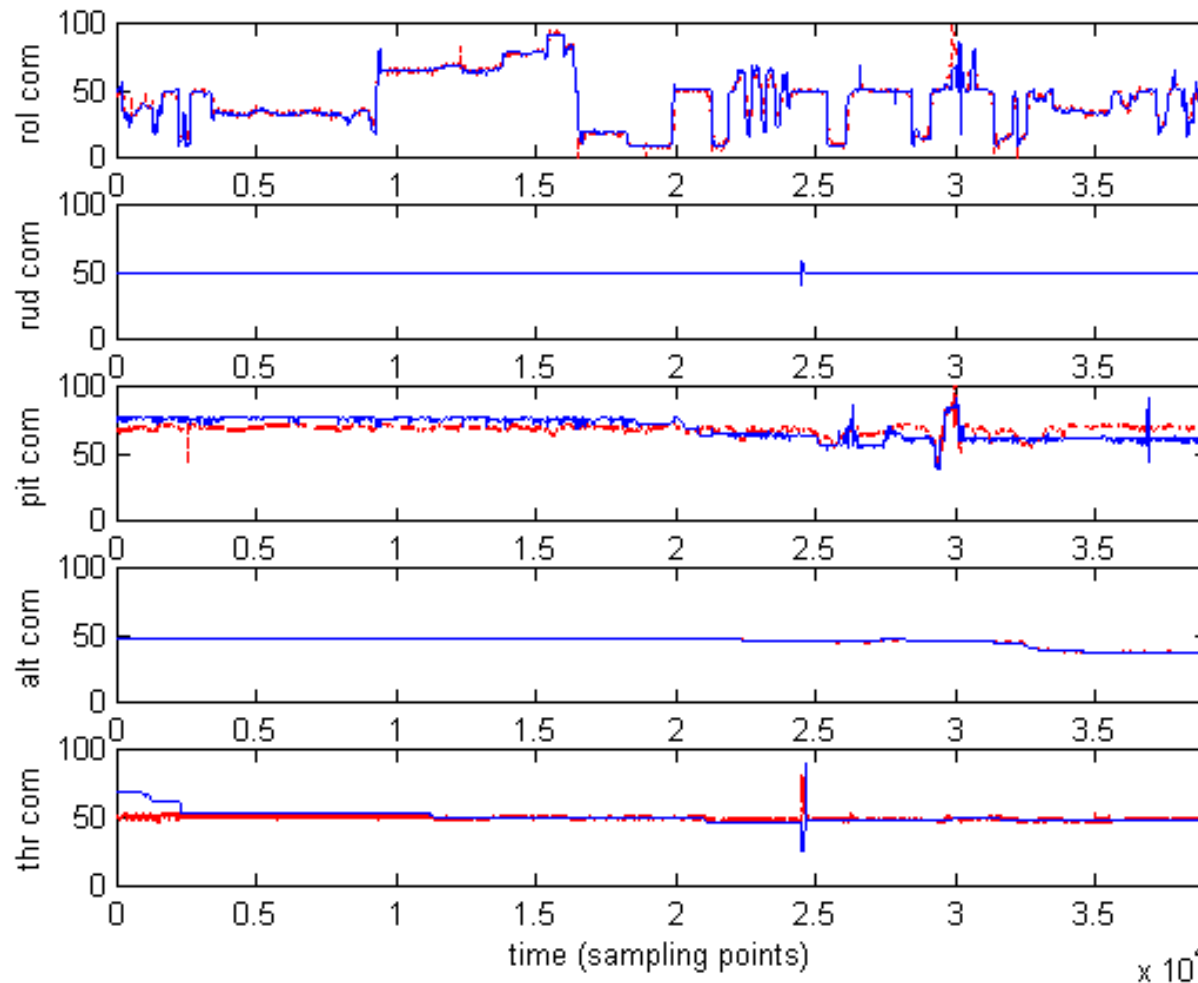
Manual commands: blue, controller commands: red

sampling rate is 37 samples/sec (approximately)

Collision Avoidance System with Fuzzy Controllers

Modular design using two FLCs

Collision Detection module: estimates collision possibilities in four directions using preprocessed radar data (assumption: radar scans in all azimuth angles).

Course Correction module: performs corrections on the desired speed, heading error and altitude error values according to the estimated collision possibilities.

Preliminary design (controllers need tuning according to the characteristics of the collision avoidance radar to be installed)

Collision Avoidance System - FLCs structure
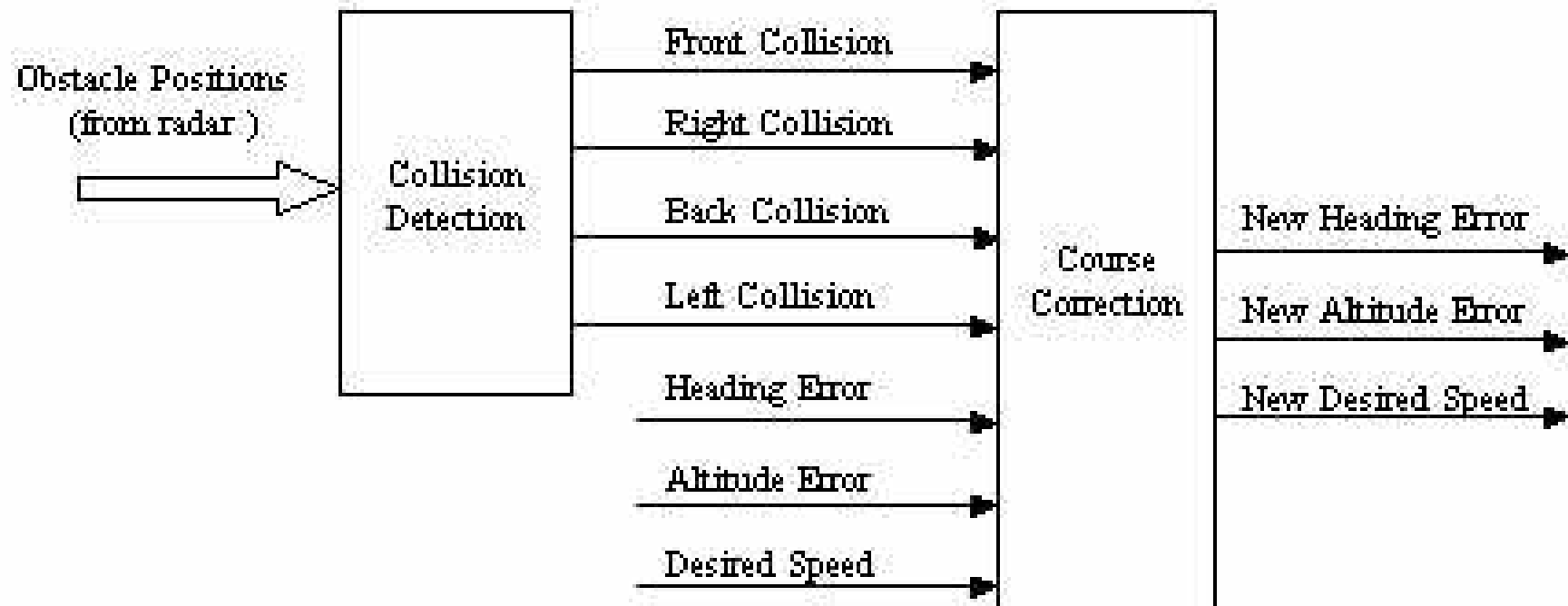
Collision Detection Controller

Collision avoidance radar (Si-Tex Radar PC), performs circular scan covering the full azimuth area (0° to 360°) in the level of flight once every 2 seconds. Effective range 24 miles. Typical NEARCHOS speed 50 m/s ➜ set range at 12 miles.

Obstacle positions data are considered to be provided as distance - azimuth pairs. The full azimuth area is partitioned in eight sectors (0°: AV heading): *s1: [0°, 45°), s2: [45°, 90°), … , s7: [270°, 315°), s8: [315°, 360°)*

From obstacle positions detected in sector ➜ select the one with minimum distance ➜ reduce amount of data points ➜ faster operation.

Distance and azimuth of the selected obstacle positions for each sector (*$s_i d$* and *$s_i az$*) are the inputs to the Collision Detection Controller.

If no obstacles are detected in sector i, *$s_i d$* is set to the max radar scan range and *$s_i az$* is set to the min azimuth of sector i.

Collision Detection Controller
Block Diagram

STN ATLAS 3 SIGMA

Collision Detection Controller-Operation Principle

STN ATLAS ELEKTRONIK
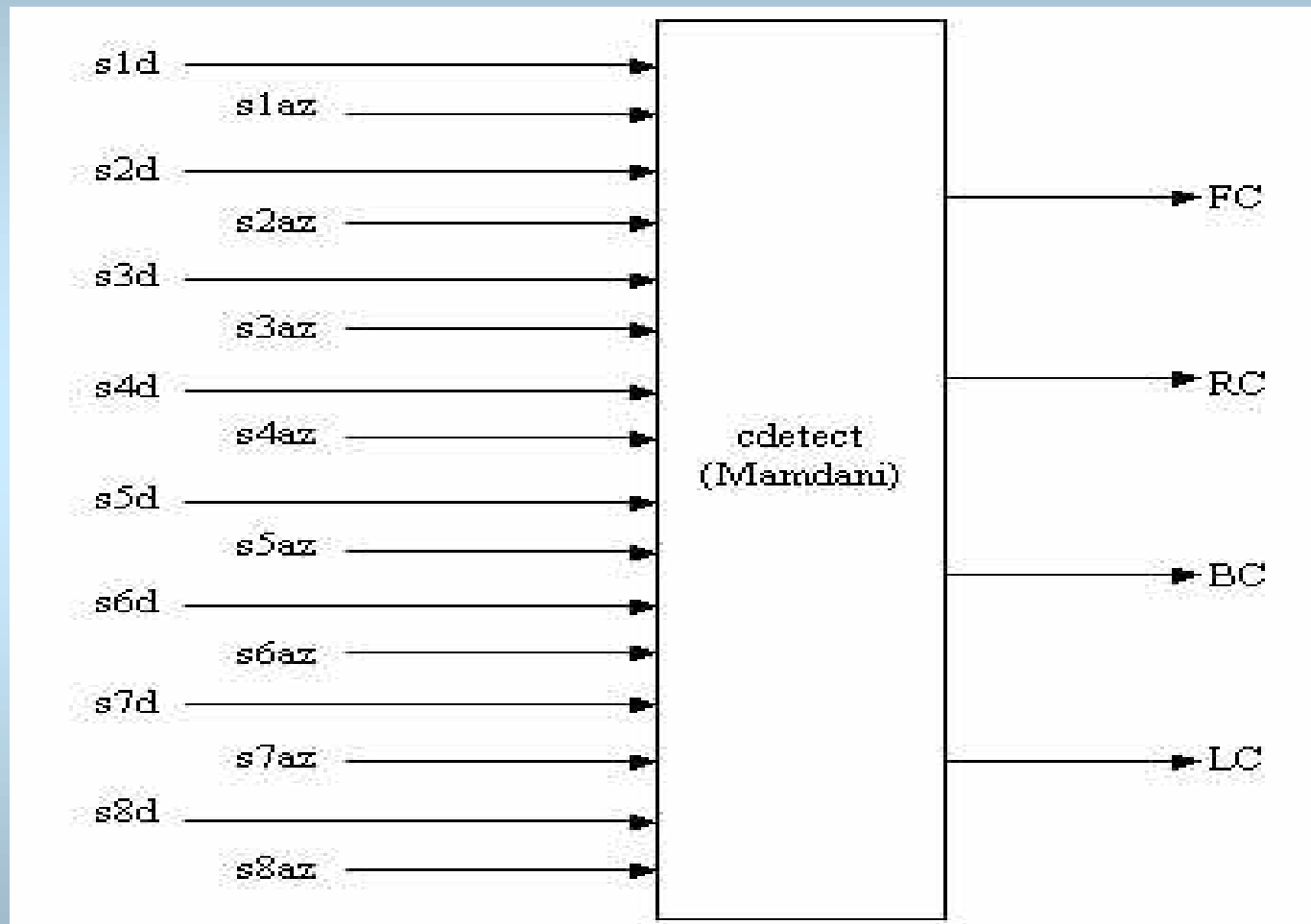
- Each of the controller outputs is a function of eight of the input variables, which are the distance and azimuth of the obstacles detected in the four sectors related to the output (collision possibility) in question

- Two primary and two secondary sectors are considered for each output

- Inputs corresponding to the primary sectors are dominant for output calculation. Secondary sectors are considered only when no obstacle is detected near in one or both of the two primary sectors

- Collision possibilities - azimuth sectors relationship:

Output	Sectors			
	Primary		Secondary	
FC	s1	s8	s2	s7
RC	s3	s2	s4	s1
BC	s5	s4	s6	s3
LC	s7	s6	s8	s5

s1: [0o, 45o), s2: [45o, 90o), … , s7: [270o, 315o), s8: [315o, 360o)

- Obstacle azimuth is not considered when obstacle distance is far

Collision Detection Controller - Inputs/Outputs

Inputs: obstacle distance and azimuth for each of the eight scan area sectors (*sid* and *siaz*, respectively, i = 1, 2, …, 8).

sid linguistic values: close, near, far. *sid* membership functions range is set to the maximum radar scan distance.

Each one of the *siaz* linguistic variables may take two linguistic values:

s1az	s2az	s3az	s4az	s5az	s6az	s7az	s8az
FR	FR	R	R	B	B	L	L
R	R	B	B	L	L	FL	FL

Outputs: Front, Right, Back, Left Collision possibilities (*FC, RC, BC, LC*, respectively)

Each of the linguistic variables *FC, RC, BC, LC* may take three linguistic values: *NP* (Not Possible), *P* (Possible), *H* (High)

Collision Detection Controller-Rule Base

- Controller type: Mamdani
- Rule base: 68 rules (17 rules for each output) of the generic form

  IF x1is A1 and x2 is A2 and … and xn is An THEN y is B

- Part of the rule base for output **FC**:

s1d	s1az	s8d	s8az	s2d	s2az	s7d	s7az	FC
close	FR	-	-	-	-	-	-	H
near	FR	near	FL	-	-	-	-	H
near	FR	far	-	-	-	-	-	P
near	FR	far	-	close	FR	-	-	H
near	FR	far	-	near	FR	near	FL	H
far	-	far	-	-	-	-	-	NP
far	-	far	-	-	-	close	FL	P
far	-	far	-	-	-	near	FL	P
far	-	far	-	close	FR	close	FL	H

Course Correction Controller – Inputs

Controller inputs: collision possibilities *FC, RC, BC, LC,* and *headerr, alterr dspeed*.

Input range for *headerr* is [-180°, 180°] (possible heading error values) - linguistic values: nb, ns, Z, ps, pb

Input range for *alterr* is [-150, 250] (in meters - according to data from NEARCHOS manual flights) - linguistic values: nb, ns, ps, pm, pb

The input range for *dspeed* is [20, 70] (in m/sec - according to data from NEARCHOS manual flights) - linguistic values: *slow*, *normal*, *fast*

Controller outputs fed to the Autonomous Navigation System: heading error, altitude error and desired speed, corrected according to the collision possibilities provided from the Collision Detection controller.

Linguistic values and membership functions of all three output variables are identical to those of the corresponding inputs, except that the range of variable *cheaderr* is [-100°, 100°] instead of [-180°, 180°] (input variable headerr). This limitation is due to the input range of the Roll and Rudder controllers of the ANS.

cdspeed output is a function of *dspeed*, *FC* and *BC* inputs

if there is no *BC* possibility, no correction in *dspeed*

if *BC* possibility is low and there is no *FC* possibility, *dspeed* increases

if *BC* possibility is small and *FC* possibility exists, no correction in *dspeed*

if *BC* possibility is high, *dspeed* increases, unless *FC* possibility is also high

cheaderr output is a function of headerr, *FC, RC* and *LC* inputs

if no collision possibility exists, no correction in *headerr*

if *FC* possibility is zero or small, corrections in *headerr* are made only if the latter dictates a turn of the AV towards a direction where a collision is possible

if *FC* possibility is high, *headerr* is corrected so as to dictate a fast turn to the direction with the lower collision possibility

if *FC* possibility is high while *LC* and *RC* possibilities are zero (or equal and small), *cheaderr* dictates a fast turn to the same direction with *headerr*

Course Correction Controller – Operation Principle, cont…

calterr output is a function of *alterr*, *FC*, *RC* and *LC* inputs

if *FC* possibility is zero, or *FC* possibility is small while both *RC* and *LC* possibilities are zero, no correction in *alterr*

if *FC* possibility is small while *FC* and *LC* possibilities exist, *alterr* increases (altitude increase is dictated)

if *FC* possibility is high, *alterr* increases at an amount analogous to *LC* and *RC* possibilities

Course Correction Controller – Rule Base

Controller type: Mamdani

Rule base: 176 rules (71 rules for *cheaderr*, 86 rules for *calterr* and 19 rules for *cdspeed*) of the generic form

IF x1is A1 and x2 is A2 and … and xn is An THEN y is B

Part of the controller rule base:

FC	RC	BC	LC	headerr	alterr	dspeed	cheaderr	calterr	cdspeed
NP	-	-	-	Z	-	-	Z	-	-
NP	P	-	-	pb	-	-	ps	-	-
P	H	-	P	pb	-	-	Z	-	-
H	P	-	H	-	-	-	pb	-	-
NP	P	-	P	-	ns	-	-	ns	-
P	H	-	P	-	ps	-	-	pm	-
H	P	-	H	-	ns	-	-	pb	-
NP	-	P	-	-	-	normal	-	-	fast
P	-	H	-	-	-	slow	-	-	normal
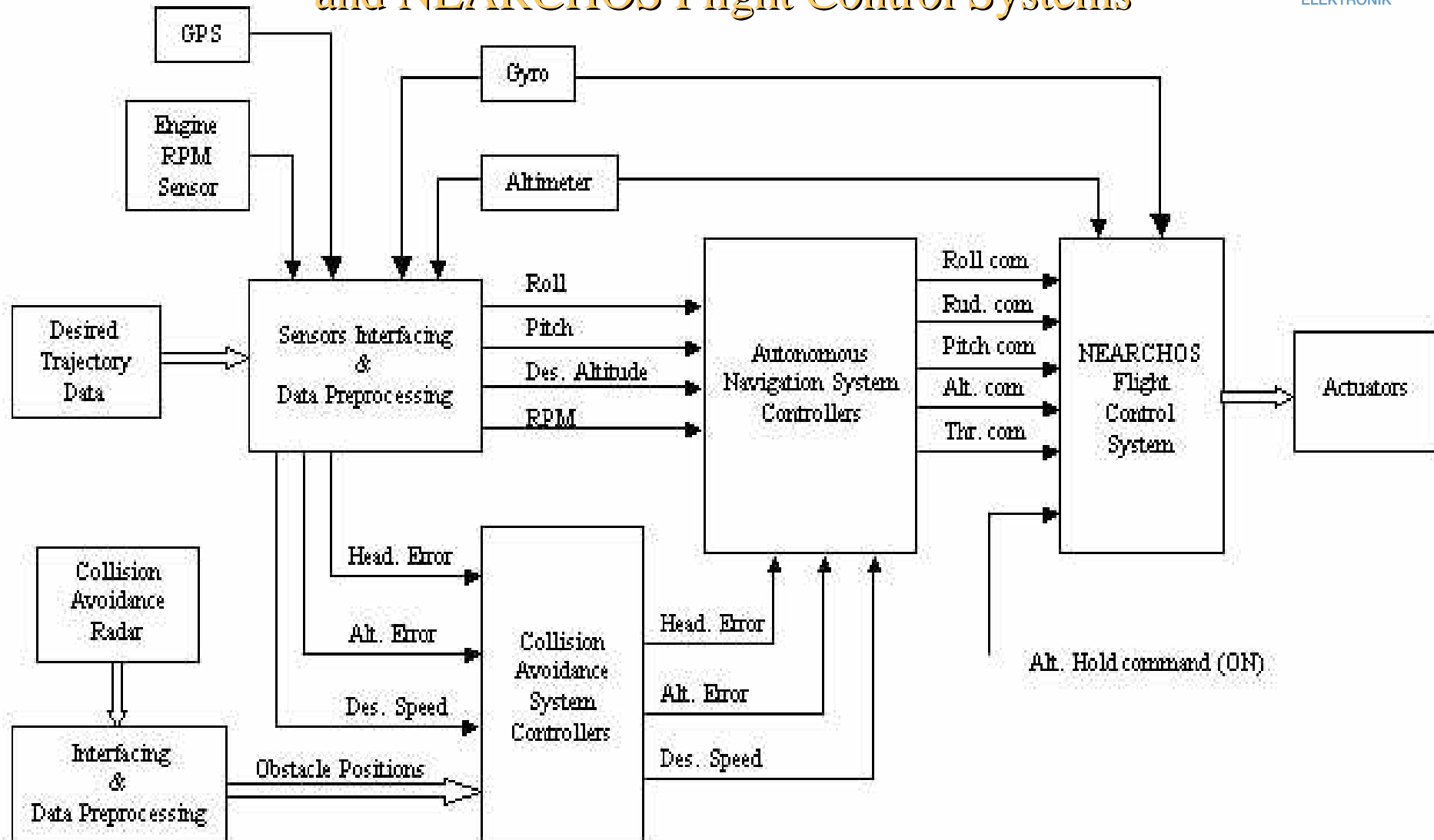
Alternative Design (model available)

Design and implementation of 3 FLCs:

guidance controller: generates navigation commands (desired roll and pitch angles, desired speed)

inputs: heading error, position error, altitude error, airspeed

lateral controller: generates commands to ailerons and rudder

inputs: desired roll angle, roll angle error, roll angular velocity, yaw angular velocity

longitudinal controller: generates commands to elevator and engine (thrust)

inputs: pitch angle error, speed error, pitch angular velocity

(First test on a Boeing 747-100 model)

Implemented SIMULINK Model
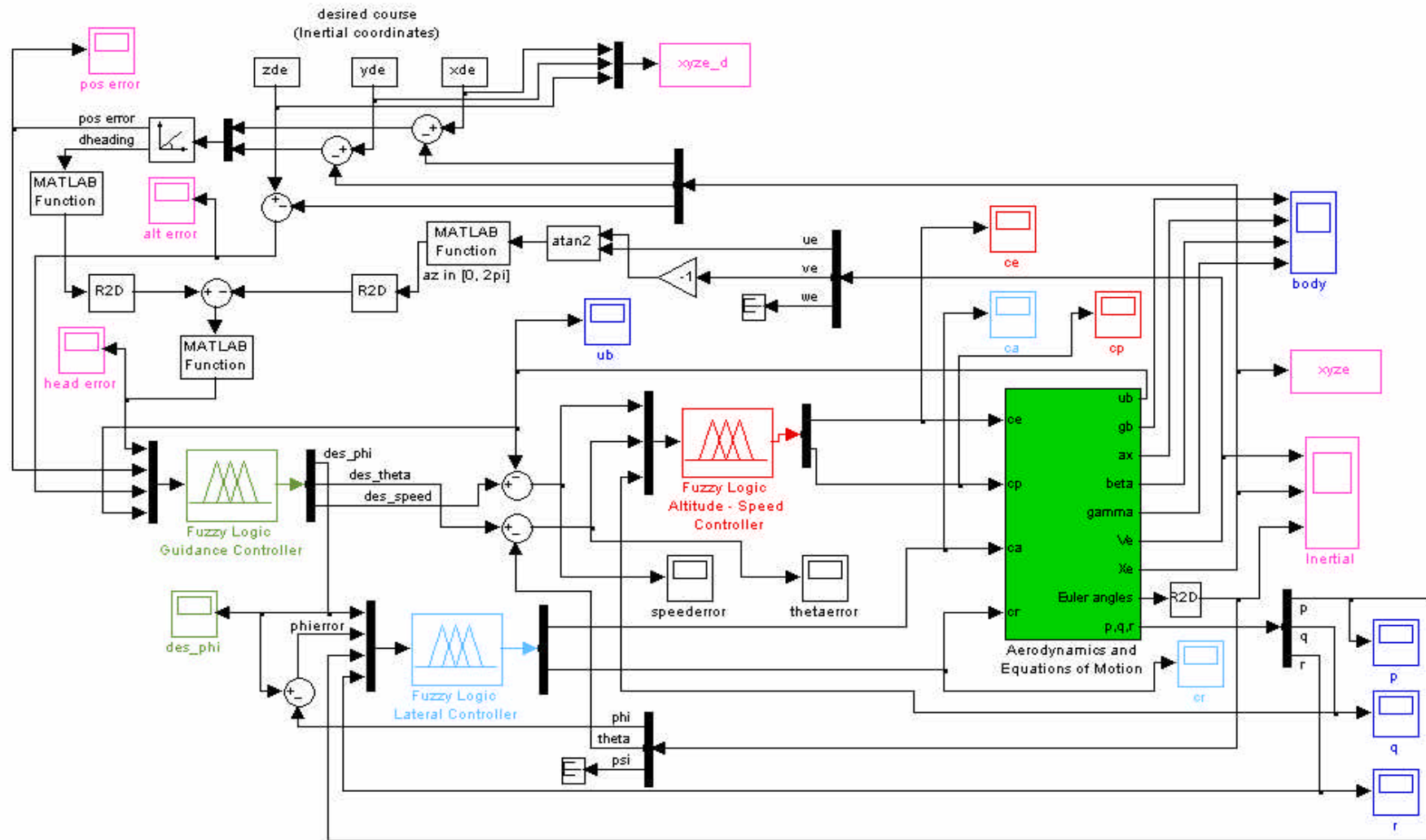
Company Information

STN ATLAS ⊕ 3 SIGMA

STN ATLAS
ELEKTRONIK

STN ATLAS-3 SIGMA

Head Office - Factory
Industrial Park, OT 23,
Chania 73200, Crete
Tel.: +308210 80133-134 & 165,
Fax.:+308210 80032
e-mail:stn-3sigmaae@cha.forthnet.gr

Athens Office
36 Messogion Ave., 4th floor,
Athens 11527, Greece
Tel.: +30107716178-180,
Fax.:+30107799418,
e-mail:3sigma@ath.forthnet.gr

STN ATLAS ELEKTRONIK

Bremen Office
Sebaldsbrucker Heerstrasse 235,
D-28305 Bremen, Deutschland,
Tel.: +49 421 457-2230/4617/4581,
Fax.:+49 421 457-4425/1923/4756